Design and analysis of the optical transceiver for mobile atmospheric laser communication

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The concept of mobile atmospheric laser communication (MALC) is introduced in this paper. Atmospheric attenuation, turbulence-induced scintillation and beam wander cause deep fades in the beam power and degrade the optical channel. The optical transceiver presented in this paper is designed for a MALC test system. Currently achievable hardware performance capabilities for the MALC terminals are used as input parameters to the analysis. A novel optical transceiver structure is designed. Link margin is analyzed using the MALC analysis software, our optical link analysis program. Data rate, bit-error rate, prime transmit power requirements, optical link margin, pulse width, background signal, aperture quality and atmospheric effects drive the optical transmitter requirements. Results are displayed as required aperture size, aperture number and the spacing between apertures for a given range and terminal moving speed. The aperture size is parameterized by data rate, transmitting optical power and wavelength. Si-APD and CCD are selected as the main receive detectors. The receiver aperture, detector size (diameter), receiver speed and sensitivity are the main factors to consider in the design of the receiver.

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Free-space optical (FSO) communication is of great interest for a variety of civilian and military applications. As the main kind of FSO communication, atmospheric laser communication has conspicuous advantages: high data rate, low transmitter power, greater directionality, smaller beam divergence, and great immunity to jamming. But it also has many research matters, especially when one or both of the atmospheric laser communication terminals are mounted on moving platforms, which is called mobile atmospheric laser communication (MALC).

As laser beams propagating, atmospheric attenuation, scintillation and beam wander become the main determinative factors of the practical range limit of MALC. Devising low-cost strategies to mitigate the effects of the atmosphere on laser-beam propagation has been a key impediment to the acceptance of MALC. High transmitting optical power and proper laser wavelength (in the optical window) can help to mitigate the effect of atmospheric attenuation. Either multiple-beam links or adaptive optics can be used to mitigate the effect of atmospheric scintillation[1]. Theoretical predictions show that a multiple-beam approach that uses less than 5-W output power can provide adequate margin in the designed optical link to compensate for atmospheric scintillation and beam wander[2]. The multiple-beam approach will cost lower and be less complicated than an adaptive optical system. Large-aperture receiver is another effective way to reduce scintillation.

The link range of our MALC test system is 4 km. The moving speed of the MALC terminal is no more than 5 m/s. The air status is light haze. Designed bit error rate (BER) is less than 10^{-6}. The whole bit rate is 194 Mb/s (155 Mb/s plus overhead).

The remainder of this paper is organized as follows. First we describe the optical transceiver structure. Then the optical link budget is calculated. The design and analysis of the transmitter is presented after that. And then the receiver system with a 20-cm telescope is described, and the detectors are also designed and introduced. The basic contents of this paper are summarized in the end.

The optical transceiver consists of four parts: transmitting optics, receiving optics, opto-electronic detectors and optical antenna servomechanism. The antenna servomechanism is made up of a gimbal and the fine steering mechanism. The gimbal provides coarse pointing of the telescopes to orient the terminal line of sight during initial acquisition and the fine steering mechanism is build in the optical assembly. The transmitting optics includes 4 communication beam-transmitting lenses, 4 beacon beam-transmitting lenses, and calibrating optics assembly. The receiving optics consists of a receiving telescope, light filters and some regulating lenses. Opto-electronic detectors include communication light detector and beacon light detector. Figure 1 shows the functional block diagram and characteristics of the optical transceiver. The front view of the optical transceiver antennas is given in Fig. 2.

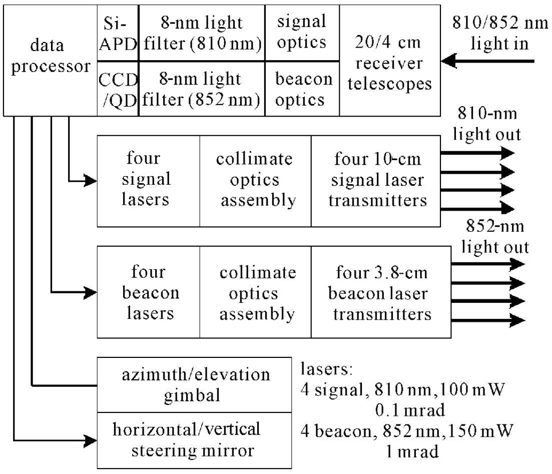

Fig. 1. Functional block diagram of the optical transceiver.

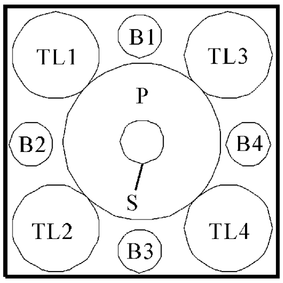

Fig. 2. Front view of the optical transceiver antennas. TL: signal lasers transmitter lens; B: beacon lasers transmitter lens; P: primary receiver mirror; S: secondary receiver mirror.

The lasers used in the MALC system are 810- and 852-nm diode lasers. The wavelengths are just outside the visible spectrum, so we expect the laser light to be attenuated in a fashion similar to visible light[3]. The transmitter optical antenna is composed of four separated 10-cm communication beam-transmitting lenses and four 3.8-cm beacon beam-transmitting lenses. The receiver antenna is a Cassegrain telescope, whose primary diameter is 20 cm with 20-cm primary focal length. The secondary diameter is 4 cm with 30-cm secondary focal length.

To achieve low burst bit error rate, sufficient margin needs to be included for atmospheric transmission. The main losses are geometric loss, atmospheric attenuation loss, scintillation loss, transmit and receive optics loss, and mispointing loss. The margin for mispointing loss (0.04 mrad) is determined by accuracy of the fine steering mirror. Assuming it as −3 dB is reasonable. The margin for scintillation loss is related to the air status and increases with range. The margin for transmit and receive optics loss (−8 dB)[5] is directly related to optical transmitting efficiency of transmit and receive optics. Attenuation and geometric losses can be computed by link margin equation[5]

$$P_{\text{received}} = P_{\text{transmitted}} 10^{-\alpha R/10} \left(\frac{d_{\text{r}}}{d_{\text{t}} + R\theta_{\text{t}}} \right)^2, \quad (1)$$

where P is power, d_{t} is the transmit aperture diameter (in meters), d_{r} is the receive aperture diameter (in meters), θ_{t} is the beam divergence (in mrad), R is the range (in kilometers), and α is the atmospheric attenuation factor (in dB/km).

For the communication light (810 nm), R=4 km, α=3 dB/km (light haze), d_{r}=0.02 m, attenuation loss is

$$\text{Loss}_{\text{a}} = 10\lg 10^{-\alpha R/10} = -3 \times 4 = -12 \text{ dB}, \quad (2)$$

and geometric loss is

$$\text{Loss}_{\text{g,signal}} = 20\lg \left(\frac{d_{\text{r}}}{d_{\text{r}} + R\theta_{\text{t,signal}}} \right) \approx -27 \text{ dB}. \quad (3)$$

In clear air and no window loss, the sum loss between the receiver and the transmitter is

$$\begin{aligned} P_{\text{r}}(\text{dBm}) - P_{\text{t}}(\text{dBm}) &= \text{Loss}_{\text{tr}} + \text{Loss}_{\text{misp}} + \text{Loss}_{\text{g}} \\ &= -8(\text{dB}) - 3(\text{dB}) - 27(\text{dB}) = -38(\text{dB}). \quad (4) \end{aligned}$$

In the MALC test system, the average communication laser power is 20 dBm. The signal power received on detector is −18 dBm in clear air. Suppose the detector sensitivity of Si-APD is −46 dBm (for BER of 10^{-6}), so the link margin for atmospheric attenuation and scintillation is 28 dB. Assume the scintillation and beam wander loss is 6 dB[4]; the margin for atmospheric attenuation can be 22 dB. Comparing with Eq. (2), the extra link margin in light haze air is 10 dB.

For the beacon, the beam divergence is

$$\theta_{\text{t,beacon}} = 1\text{mrad}, \quad (5)$$

and the geometric loss is

$$\text{Loss}_{\text{g,beacon}} = 20\lg \left(\frac{d_{\text{r}}}{d_{\text{r}} + R\theta_{\text{t,beacon}}} \right) \approx -46 \text{ dB}. \quad (6)$$

In clear air and no window loss, the sum loss between the receiver and the transmitter is −57 dB. The average beacon laser power is 22 dBm, and the beacon power received on CCD is −34 dBm in clear air. If the detector sensitivity of CCD is −57 dBm (available), the link margin for atmospheric attenuation is 16 dB. Comparing with Eq. (2), the link margin in light haze air is 4 dB. To some extent, multiple-beam approach will reduce atmospheric attenuation and attenuation loss.

Overlapping of mutually incoherent beams in the far field can be used to reduce the signal fades and fluctuates at the receiver. Four 810 nm diode laser beams from four 10-cm aperture lenses and four 852-nm diode laser beams from four 3.8-cm aperture lenses build the transmitter. For eye safety, the communication laser output power is designed as 100 mW and the beacon laser output power is 150 mW.

The aperture of each beam-transmitting lens is designed as 10 cm and the spacing between any two neighboring transmitting lenses is 10.21 cm (Fig. 2). The aperture size d_{t} determines the beam divergence. The beam divergence is given by

$$\theta_{\text{t}} = 1.22 \cdot \beta \cdot \lambda / d_{\text{t}}, \quad (7)$$

where d_{t} is the transmit aperture diameter, β is the beam quality factor. Assuming $\beta = 1.5$ and $\theta_{\text{t}} = 0.1$ mrad, d_{t} should be larger than 0.015 m at 810 nm. Considering the actual laser beam quality (worse), the transmitter aperture is selected as 10 cm, which is several times of the ideal predicted value.

Reference [7] gives the experimental results of the intensity probability distribution for different number of transmitter apertures. The intensity fluctuation is large for the one laser case and best fits to a decaying exponential distribution. With the number of lasers (different apertures) increase, the intensity fluctuations decrease and are closer to log normal distribution[7]. Apparently multiple-beam approach has mitigated the effect of atmospheric scintillation. But with the aperture number increasing, the complexity of the optics also increases. As a result of tradeoff, 4 transmitting apertures are used for communication and beacon light[1], respectively.

In order to keep the beams incoherent mutually in the receiving field, the spacing between apertures should be larger than the atmospheric coherence length r_0.

Roughly, r_0 is scaled as $\sqrt{\lambda R}$[7], where λ is the laser wavelength and R is range. At the link range of 4 km, this corresponds to 5.69 cm at 810 nm, and 5.84 cm at 852 nm. So the spacing between the communication beam-transmitting lenses is designed as 10.21 cm.

The beacon beam-transmitting divergence determines the difficulty of beam acquisition and tracking. It is designed as 1 mrad. Assuming $\beta = 1.5$ and the beam divergence $\theta_{\mathrm{t,beacon}} = 1$ mrad, the limited aperture size of the beacon beam-transmitting lenses can be computed by Eq. (7),

$$d_{\mathrm{t,b,min}} = 1.22 \cdot 1.5 \cdot 0.852/\theta_{\mathrm{t,beacon}} = 1.56\ \mathrm{mm}. \qquad (8)$$

Considering the actual laser quality, the aperture of the beacon beam-transmitting lenses is designed as 3.8 cm (As analyzed above, the spacing between beacon transmitter apertures should be larger than 5.84 cm). We design the spacing as 16.8 cm. It is sufficient to keep the beacon beams incoherent mutually in the receiving field.

The important aspects of the receiver are aperture size, field of view (FOV), and the characteristics of detectors. The aperture size determines the amount of light collected on the receiver and the FOV determines the amount of background light and the difficulty for beam alignment. The size, speed and sensitivity are the main factors to consider for detectors[8].

A collecting aperture that is much larger than the spatial scale of the scintillation provides an averaging effect of the localized fluctuates and fades to improve the BER performance. Reference [7] has validated the aperture averaging effect, shown in Fig. 3. Comparing the curves in Fig. 3, we find the intensity probability distribution is nearer to log normal distribution with larger receiver aperture. In the case we study, the link range (4 km) is shorter than the link range (10.4 km) in Fig. 3, and the intensity fluctuation is weaker. So 20-cm aperture is sufficient to support the averaging effect.

The secondary diameter, which is designed as 4 cm, is related to central obscuration. We hope the receiver telescope has low obscuration (below 5%), high optical quality, low stray light level, high optical transmittance (> 0.9) and high antenna gain. To meet these specifications, a dioptric collimator is designed behind the telescope. After the lights pass through the collimator, communication light and beacon light are separated and transmitted through different paths.

For beacon beam acquisition, we hope the receiving FOV of the beacon light is as large as possible. FOV can be calculated by

$$\mathrm{FOV} = 2 \arctan \frac{d_{\mathrm{rd}}}{2f}, \qquad (9)$$

where d_{rd} is the receive detector diameter, and f is the equivalent focal length. For the communication light, the FOV is 1 mrad, and the equivalent focal length is 0.4 m (assuming d_{rd}=0.2 mm). For the beacon light, the FOV of CCD is 8×2 mrad. The equivalent focal length is 0.25 m (CCD is selected as 256 pixels by 64 pixels; the valued square is 10×2 mm^2). Though the FOV can be larger, background light becomes the impediment. In order to lower the background light signal, nanometer band pass filter (8 nm) is used before the detectors.

Two types of communication light detectors are often used in FSO system: PIN and APD. PIN detector is a cheaper detector but has no internal gain, while the APD is expensive but more sensitive detector with great internal gain. So Si-APD is selected as the communication light detector. The detecting and processing method for the APD signals has been discussed in Ref. [9].

Reference [8] has discussed the selecting method of detector size, receiver speed and sensitivity. Based on the method, the diameter of Si-APD is designed as 0.2 mm. The speed requirement for the detector is based on the 5 ns pulse width (194 Mb/s), so a Si-APD with 2 ns rise/fall time (90 − 10%) is enough response to the incoming pulse modulation. Based on the analysis in link margin calculations, the sensitivity of the Si-APD is −46 dBm. The kind of Si-APD is now available.

Comparing with optoelectronic diode array and PSD, CCD detector has characteristics of linear scanning, high space resolution and wide dynamic range. So it is chosen for the beacon light detecting. The CCD is designed as 256 pixels by 64 pixels with 10×2 mm^2 area. The exposure time is less than 0.02 s, and the dynamic range is 500:1. The relation between acquisition time and the CCD parameters for different scan methods will be introduced in other paper. It is related to the scanning range (azimuth: 435 mrad, elevation: 40 mrad), terminal moving speed (5 m/s), acquisition probability requirement (> 95%) and terminal positioning accuracy (20 m). The designed acquisition time is no more than 5 minute, and the pointing accuracy is ±0.02 mrad.

The optical transceiver necessary to meet the demand of high data rate MALC has been designed for a MALC test system. The novel optical transceiver structure with multi-beam transmitting and large aperture receiver is put forward. Based on high gain Si-APD and high resolution CCD, the optical transceiver will achieve 194 Mb/s data rate with a BER of 10^{-6}. The link margin is calculated with the available hardware performance. The performance of the optical transceiver is quantified as pointing accuracy, link margin, the sensitivity of the receiver and link setup time.

Future designs are proposed as multi-angle diversity receiver, array APD detectors and adaptive optical transceiver with internal gimbal-less pointing and tracking.

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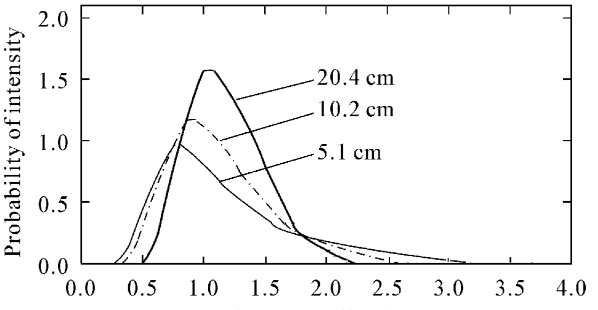

Fig. 3. Probability versus intensity for receiver apertures sizes of 20.4, 10.2 and 5.1 cm (10.4 km).

References

1. D. T. Ma, Z. W. Zhuang, and J. B. Wei, Chin. J. Lasers **29,** 277 (2002).
2. K. E. Wilson, P. R. Leatherman, and R. Cleis, *TDA Progress Report* (42-131 Jet Propulsion Laboratory, Pasadena, California, 1997) p. 1.
3. E. Korevaar, J. Schuster, and H. Hakakha, Proc. SPIE **3266,** 153 (1998).
4. I. I. Kim, E. Woodbridge, and V. Chan, Proc. SPIE **3266,** 209 (1998).
5. S. Bloom and J. Schuster, *WCA Technical Symposium* (San Jose, CA, Jan. 14, 2003).
6. R. M. Gagliardi and S. Karp, *Optical Communications* (John Wiley, New York, 1976) p. 167.
7. I. I. Kim, H. Hakakha, P. Adhikari, Proc. SPIE **2990,** 102 (1997).
8. G. G. Ortiz, J. V. Sandusky, and A. Biswas, Proc. SPIE **3932,** 127 (2000).
9. W. L. Hua, D. T. Ma, and J. B. Wei, Chin. J. Lasers (accepted).